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Abstract

Four different NHC ligands have been coordinated to Pt(II) centres; for the first time cyclometallation of the NHC ligand was observed, but only when the platinum centre had a DMSO and two methyl co-ligands. Cyclometallation resulted in the exclusive formation of five-membered rings, and the absence of any double cyclometallation reactions with appropriate ligands rules out the possibility of an oxidative addition type mechanism for the cyclometallation reaction.

Introduction

In the past ten years the nitrogen stabilised heterocyclic carbene (NHC) ligand has progressed from being an academic curiosity to its present ubiquity: it is now considered as a versatile ligand that is often used in preference to the more traditional phosphine. 1 Electronically, the NHC ligand has often been considered to be a better $\sigma$ donor, and a weaker $\pi$ acceptor, than the phosphine ligand, 2 though contrary evidence regarding their $\pi$ acceptor ability is available. 3 Relatively simple synthetic procedures leading to precursor imidazolium salts have been elucidated, 4 and many routes that allow the introduction of an NHC ligand to a metal centre have been developed. The reaction of imidazolium salts with silver oxide giving an NHC complex of silver, which serves as a useful trans-metallating reagent, has proved particularly popular, 5-8 and we use it in this paper. Other interesting methods include the utilisation of an electron-reservoir complex, together with air, to generate NHCs, 9 or the use
of imidazolium-2-carboxylates which lose CO$_2$ to generate NHCs,\textsuperscript{10} though, increasingly, direct reaction of the imidazolium salt with the metal has found favour.\textsuperscript{11-14} More recently, NHC ligands have been shown not to be innocent spectators, but reactive intermediates themselves, with a number of new products being formed.\textsuperscript{15, 16}

Whilst most the studies on catalytically active systems have their emphasis on palladium based chemistry,\textsuperscript{17} platinum complexes are also of interest. Amongst other uses, platinum complexes with NHC ligands have been used for the reductive cyclization of diynes and enynes\textsuperscript{18}, the catalytic diboration of unsaturated molecules\textsuperscript{19} and the tandem hydroboration-cross coupling reaction.\textsuperscript{20} Thus the clean, high yielding synthesis of NHC platinum complexes is of considerable current interest. Cyclometallation\textsuperscript{21} of NHC ligands has been reported many times, but to the best of our knowledge none of these examples are cycloplatinated complexes. By contrast, a search of the Cambridge Crystallographic Database\textsuperscript{22} reveals fifty-eight structurally characterised cyclopalladated NHC complexes; it is of relevance to note that none of these complexes have a three or four membered cyclometallated ring, only six\textsuperscript{23, 24} have a five membered ring, forty-two have a six membered ring, twelve a seven membered ring and eight an eight membered ring.

**Results and Discussion**

In order to establish some of the principles behind the cycloplatination of NHC ligands, we studied the reactivity of four different imidazolium salts 1 with platinum sources, Scheme 1.

<table>
<thead>
<tr>
<th>Scheme 1</th>
<th>1a: $R = 4$-F-phenyl, $R' = $ Me</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1b: $R = R' = 4$-F-phenyl</td>
</tr>
<tr>
<td></td>
<td>1c: $R = 4$-F-phenyl, $R' = 4$-F-benzyl</td>
</tr>
<tr>
<td></td>
<td>1d: $R = $ Me, $R' = 4$-F-benzyl</td>
</tr>
</tbody>
</table>

Using our previously described methodology,\textsuperscript{25} we can selectively introduce either one or two NHC ligands at a platinum centre, via silver complexes, Scheme 2.
We had hoped that we could induce one or both of the complexes 3 or 4 to undergo a cyclometallation reaction, but we were unable to find suitable conditions and reagents to facilitate such transformations. The reagent PtMe$_2$(DMSO)$_2$ has been reported$^{26}$ to induce facile cyclometallation reactions and we thus tried it. Reaction of the silver NHC complexes 2 with PtMe$_2$(DMSO)$_2$ has not previously been documented, but we can report that it works well as another method of selectively introducing a single NHC ligand to a platinum(II) centre, giving excellent yields, Scheme 3.

A *cis* orientation of the two methyl groups in complexes 5 can clearly be established from the $^1$H NMR as two signals (relative integral three) are seen for these groups. Different couplings from these protons to the central platinum are also seen: the $^2J_{Pt-H}$ for the methyl *trans* to the NHC is typically 60 Hz, whereas that of the methyl *trans* to the DMSO is typically 80 Hz; such differences are readily accounted for by the differing *trans* influences of the NHC and DMSO ligands. In the complexes with unsymmetrical NHC ligands (i.e. R $\neq$ R’) two signals (each of relative integral three) are seen for the DMSO protons at room temperature, consistent with the plane of the NHC ligand being perpendicular to the coordination plane of the platinum, together with restricted rotation about the NHC–Pt bond.$^{25,27}$

Gentle heating of the new complexes 5a-c results in a C-H activation reaction of the phenyl ring, similar to that seen before.$^{26,28,29}$ Cyclometallated products 6a-c are now seen, presumably accompanied by the elimination of methane, Scheme 4.
The new complexes 6a-c are easily identified by NMR spectroscopy. In the $^1$H NMR only one Me group bonded directly to platinum is observed, all six protons of the DMSO become equivalent and the coupling pattern of the protons on the phenyl group change (from two sets of two protons, to three individual resonances; one with Pt satellites). The $^{19}$F NMR shows a signal for a fluorine with platinum satellites, consistent with a cyclometallation.

The platinum bound methyl groups in 6a-c are confirmed to be trans to the NHC ligand via a series of NOE experiments; if we take the R’ = Me complex 6a as a representative example, we can see NOE interactions between the Pt-Me and the cyclometallated ring, between the Pt-Me and the DMSO protons and between the DMSO protons and the R’ group (and vice versa, in each case). Within the coordination sphere of the platinum in 6 this geometry is the one we would expect as it is the arrangement without the aryl and alkyl carbon donors being trans to each other; similar to other work, it puts the alkyl carbon donor trans to the NHC ligand.

The cyclometallation reaction brings the plane of the NHC ring into alignment with that of the coordination plane of the platinum and renders the all protons of the DMSO co-ligand equivalent. Relatively small couplings (typically 15 Hz) from the platinum to the DMSO protons are observed in both complexes 5 and 6, consistent the DMSO being trans to a high trans-influence ligand in both complexes. However, relatively large (around 70 Hz) three bond couplings from the central platinum to the protons ortho to both the Pt and the F in cyclometallated ring are seen in complexes 6. Previously we have seen couplings in the range of 24-55 Hz for this type of proton, with coupling this large only when the cyclometallated ring is trans to an agostic interaction. The coupling of the platinum to the fluorine is also larger than normal, again similar to that seen in agostic complex.

In principle the single cyclometallation of complex 5c could have taken place in one of two ways: either the phenyl ring or the benzyl ring attached to the NHC could have been activated; the possibility also exists for a double cyclometallation. In practice only one cyclometallated product was ever observed, even upon prolonged heating. This single product was confirmed to be the one in which only the phenyl ring was cyclometallated via a series of NOE experiments: the clearly distinct benzyl and DMSO protons were shown to be close to each other and, crucially, both showed enhancements upon irradiation of the signals for the non-cyclometallated ring (and vice versa) with no enhancements observed between these
signals and the cyclometallated ring. The absence of any product containing a cyclometallated benzyl group is consistent with the observation of no reaction at all when complex 5d was heated in benzene, even when that heating was maintained for a week.

Clearly, therefore this methodology gives rise to a preference for cyclometallation of a phenyl ring (to give a five-membered metallacycle) over the cyclometallation of a benzyl group (to give a six-membered metallacycle); it should be noted that both metallation reactions involve the activation of an sp² hybridised C-H bond. Such an outcome is very much in line with historical precedent: five-membered metallacycles account for the majority of published examples. However, given that structurally characterised six-membered NHC-palladacycles outnumber five-membered NHC-palladacycles forty-two to six, we can assume there would be nothing inherently unstable about a six membered NHC-platinacycle, and the reason we do not observe them is in someway related to the kinetics of the pathway leading to our products. Extended heating of compounds 6b or 6c did not result in any double cyclometallation. Given the observations above, regarding complex 5d, the lack of any subsequent reaction with 6c is perhaps not surprising. The second cyclometallation of compound 6b would, however, lead to a second five membered ring and, by analogy with pyridine and phosphine systems, ought to be accessible. Once again, it is presumably the reaction pathway that inhibits the reaction, rather than the inherent stability of the product.

There are two widely accepted extremes of mechanisms for C-H activation reactions of this type: an oxidative addition type mechanism, route A, Scheme 5 and an “electrophilic” mechanism that has many similarities to σ-bond metathesis, route B, Scheme 5. Evidence for both types of process has been presented for platinum(II).

It is worth considering one of these reports in more detail as it deals with the cycloplatination of a complex rather similar to ours: an o-tolylphosphine is coordinated to a dimethyl platinum centre that also has a DMSO ligand. Strong evidence is presented that the DMSO ligand dissociates prior to oxidative addition of the sp³ C-H bond of the phosphine, giving a methyl hydride which then eliminates methane with the concomitant recoordination of the DMSO. However, if such a process operated in our reactions, it would be hard to see
why the cyclometallation of 5d did not take place, or why complex 6b did not undergo a second cyclometallation. Conversely, if we were to expect the cyclometallation of the second phenyl ring of 6b to go via the electrophilic route, with some sort of concerted coupling of the hydrogen with the methyl group, it would be imperative that the methyl group be adjacent to the phenyl ring. Since it is not we can easily understand a lack of reactivity if this route were operational.

The lack of any cyclometallation of the benzyl groups is harder to understand, but there ought to be no reason why an oxidative addition type reaction could not take place: the six membered ring formed ought to be perfectly stable; a concerted process would require the formation of a slightly bigger ring in the transition state, and perhaps that is unfavourable.

Whilst we have not undertaken an exhaustive study of our reaction, it seems likely, therefore, that our cycloplatinations do go via a mechanism that is closer to the electrophilic route than it is to the oxidative addition route. Whether the difference between our chemistry and that of the example noted above is due to the nature of the C-H bond being activated (in our case an sp\(^2\) hybridised carbon, in theirs an sp\(^3\)) or a function of the ligand (in our case an NHC, in their case a phosphine) is currently unclear, and we propose to investigate the matter further.

**Conclusions**

Four different NHC ligands have been coordinated to Pt(II) centres. Three of the four ligands underwent cyclometallation reactions but only when the platinum centre had a DMSO and two methyl co-ligands. These products represent the first reported examples of cycloplatinated NHC ligands as our reaction conditions resulted in the exclusive formation of five-membered metallacycles. The absence of any double cyclometallation reactions with appropriate ligands rules out the possibility of an oxidative addition type mechanism for the cyclometallation reaction.

**Experimental**

All chemicals were used as supplied, unless noted otherwise. All NMR spectra were obtained on a Bruker Avance 400, 500 or 600 in CDCl\(_3\), CD\(_2\)Cl\(_2\) or C\(_6\)D\(_6\); \(^1\)H and \(^19\)F spectra were observed directly and are referenced to external TMS or CFCl\(_3\), respectively. \(^{195}\)Pt chemical shifts quoted are taken from 2D \(^1\)H-\(^{195}\)Pt HETCOR spectra and are referenced to external Na\(_2\)PtCl\(_6\). Elemental analyses were performed by Warwick Analytical Services.

Imidazolium salts were synthesised via literature routes: 1a via the copper catalysed coupling of 4-fluoro-phenyl boronic acid with imidazole, followed by reaction with MeI; 1b via the condensation of 4-fluoro-aniline with glyoxal, followed by reaction with chloromethylethyl
ether; 1c via the copper catalysed coupling of 4-fluoro-phenyl boronic acid with imidazole, followed by reaction with 4-fluoro-benzyl bromide; 1d via the reaction of methylimidazole with 4-fluoro-benzyl bromide. Silver NHC salts were then prepared via the reaction of imidazolium salt with silver oxide in DCM.\textsuperscript{5,6,8}

**Synthesis of the [Pt(NHC)(DMSO)(Me)] complexes (5)**

Full details are given for 5a only: analogous complexes were prepared in a similar manner. To a solution of 62 mg (0.151 mmol) of 2a in CH\textsubscript{2}Cl\textsubscript{2} (20 ml), was added 57.5 mg (0.151 mmol) of [Pt(Me)\textsubscript{2}DMSO\textsubscript{2}]. The mixture was stirred at room temperature, under nitrogen, for six hours; the colour changed quickly to a milky-white suspension. The mixture was filtered through celite to give a colourless solution, which was then concentrated to small volume and treated with petrol ether to give a white precipitate, which was then collected to give analytically pure material. Yield 79%.

**5a** Anal. Calcd. for C\textsubscript{14}H\textsubscript{19}FN\textsubscript{2}OPtS: C, 35.07%, H, 4.41%, N, 5.84%. found: C, 34.74%, H, 4.45%, N, 5.65%.

NMR (C\textsubscript{6}D\textsubscript{6}) \(\delta\)H: 7.6 (2H, dd, J = 8.8, J\textsubscript{F-H} = 4.8 Hz, H\textsubscript{o}), 6.68 (2H, t, J = J\textsubscript{F-H} = 8.6 Hz, H\textsubscript{m}), 6.26 (1H, d, J = 2, J\textsubscript{Pt-H} = 6.6 Hz, H\textsubscript{imid}), 5.96 (d, 1H, J = 2, J\textsubscript{Pt-H} = 7 Hz, H\textsubscript{imid}), 3.41 (3H, s, Me\textsubscript{NHC}), 2.45 (3H, s, J\textsubscript{Pt-H} = 15 Hz, DMSO), 2.03 (3H, s, J\textsubscript{Pt-H} = 15 Hz, DMSO), 0.56 (3H, s, J\textsubscript{Pt-H} = 81 Hz, Me); \(\delta\)F: -114.06; \(\delta\)Pt: -3914.

**5b** Anal. Calcd. for C\textsubscript{19}H\textsubscript{22}F\textsubscript{2}N\textsubscript{2}OPtS: C, 40.78%, H, 3.96%, N, 5.01%. Found: C, 40.21%, H, 4.21%, N, 4.82%.

NMR (C\textsubscript{6}D\textsubscript{6}) \(\delta\)H: 7.98 (2H, dd, J = 8.9, J\textsubscript{H-F} = 5 Hz, H\textsubscript{o}), 7.63 (2H s, H\textsubscript{imid}), 7.30 (2H, t, J = J\textsubscript{F-H} = 8.7 Hz, H\textsubscript{o}), 2.56 (6H, s, J\textsubscript{Pt-H} = 15 Hz, DMSO), 0.1 (3H, s, J\textsubscript{Pt-H} = 82 Hz, Me), -0.24 (3H, s, J\textsubscript{Pt-H} = 65 Hz, Me); \(\delta\)F: -115.54; \(\delta\)Pt: -3905.

**5c.** Anal. Calcd. for C\textsubscript{20}H\textsubscript{24}F\textsubscript{2}N\textsubscript{2}OPtS: C, 41.88%, H, 4.22%, N, 4.88%. Found: C, 41.40%, H, 4.29%, N, 4.89%.

NMR (C\textsubscript{6}D\textsubscript{6}) \(\delta\)H: 7.66 (2H, dd, J = 8, J\textsubscript{H-F} = 4.4 Hz, H\textsubscript{o}), 7.07 (2H, dd, J = 8, J\textsubscript{H-F} = 4.6 Hz, H\textsubscript{o}), 6.80 (2H, t, J = J\textsubscript{F-H} = 8 Hz, H\textsubscript{m}), 6.71 (2H, t, J = J\textsubscript{F-H} = 8 Hz, H\textsubscript{m}), 6.36 (1H, d, J = 2 Hz, H\textsubscript{imid}), 6.12 (1H, d, J = 2 Hz, H\textsubscript{imid}), 5.89 (d, 1H, J = 14 Hz, benzyl), 4.72 (1H, d, J = 14 Hz, benzyl), 2.33 (3H, s, J\textsubscript{Pt-H} = 14 Hz, DMSO), 2.03 (3H, s, J\textsubscript{Pt-H} = 15 Hz, DMSO), 1.13 (3H, s, J\textsubscript{Pt-H} = 82 Hz, Me), 0.48 (3H, s, J\textsubscript{Pt-H} = 64 Hz Me); \(\delta\)F: -113.80 (1F, s), -114.24 (1F, s); \(\delta\)Pt: -3919 ppm.

**5d.** Anal. Calcd. for C\textsubscript{15}H\textsubscript{23}FN\textsubscript{2}OPtS: C, 36.51%, H, 4.70%, N, 5.68%. Found: C, 36.00%, H, 4.59%, N, 5.45%.

NMR (C\textsubscript{6}D\textsubscript{6}) \(\delta\)H: 6.94 (2H, dd, J = 8.8, J\textsubscript{F-H} = 5.4 Hz, H\textsubscript{o}), 6.73 (2H, t, J = J\textsubscript{F-H} = 8.67 Hz, H\textsubscript{m}), 5.98 (1H, d, J = 1.9 Hz, H\textsubscript{imid}), 5.92 (1H, d, J = 1.9 Hz, H\textsubscript{imid}), 5.55 (d, 1H, J = 15 Hz, benzyl), 4.89 (1H, d, J = 15 Hz, benzyl), 3.39 (3H, s, Me\textsubscript{NHC}), 2.51 (3H, s, J\textsubscript{Pt-H} = 14.7 Hz,
DMSO), 2.38 (3H, s, J_Pt-H = 14.8 Hz, DMSO), 1.14 (3H, s, J_Pt-H = 81 Hz, Me), 0.67 (3H, s, J_Pt-H = 63 Hz Me); δ_F: -115.04; δ_Pt: -4002ppm.

**Synthesis of the \([Pt(NHC-H)(DMSO)Me]\) complexes (6)**

Full details are given for 6a only: analogous complexes were prepared in a similar manner. A solution of 42 mg of \([Pt(NHC-DMSOMe)_2]\), 5a, was heated (50°C, 2hr), with stirring, in freshly distilled benzene. During this time the colour of the solution changed from colourless to yellow. Then the solution was concentrated to small volume and treated with pet ether (40-60) to precipitate the product. The solid was then filtered off to give an analytically pure product as a yellow solid. Yield 69%.

6a. Anal. Calcd. for C_{13}H_{17}FN_2OPtS: C, 33.69%, H, 3.70%, N, 6.04%. found: C, 33.77%, H, 3.44%, N, 6.11%.

NMR (C_6D_6) δ_H: 8.07 (1H, dd, J_H-F = 10.2, J = 2.4, J_Pt-H = 71 Hz, H_o), 6.65 (1H, td, J_H-F = J = 8.2, J = 2.5 Hz, H_m), 6.43 (1H, dd, J = 8.6, J_H-F = 5.0 Hz, H_o), 6.27 (1H, s, H_imid), 5.65 (1H, s, H_imid), 3.57 (3H, s, Me_NHC), 2.45 (6H, s, J_Pt-H = 16 Hz, DMSO), 0.63 (3H, s, J_Pt-H = 64 Hz, Pt-Me); δ_F: -118.5 (1F, s), δ_Pt: -4210ppm.

6b. Yield 74%. Anal. Calcd. for C_{18}H_{18}F_2N_2OPtS: C, 39.78%, H, 3.34%, N, 5.15%. found: C, 40.12%, H, 3.43%, N, 4.95%.

NMR (D_6-acetone) δ_H: 7.95 (1H, d, J = 2 Hz, H_imid), 7.67 (2H, dd, J_H-F = 8.8, J = 4.7 Hz), 7.52 (1H, d, J = 2 Hz, H_m), 7.45 (1H, dd, J_H-F = 8.6, J = 4.5 Hz), 7.42 (1H, dd, J_H-F = 8.2, J = 2.0, J_Pt-H = 65 Hz), 7.31 (2H, t, J = J_H-F = 8 Hz), 6.83 (1H, td, J = J_H-F = 8.5, J = 1.8 Hz), 2.86 (6H, s, J_Pt-H = 16 Hz, DMSO), 0.45 (s, 3H, J_Pt-H = 64 Hz Me); δ_F: -115.49 (1F, s), -120.01 (1F, s, J_Pt-F = 57 Hz); δ_Pt: -4152ppm.

6c. Anal. Calcd. for C_{19}H_{20}F_2N_2OPtS: C, 40.93%, H, 3.62%, N, 5.02%. found: C, 40.68%, H, 3.61%, N, 5.32%.

NMR (C_6D_6) δ_H: 8.10 (1H, dd, J = 3, J_H-F = 10, J_Pt-H = 70 Hz, H_o), 7.50 (2H, dd, J = 8, J_H-F = 4.6 Hz), 7.20 (1H, dd, J = 9, J_H-F = 5 Hz), 6.75 (1H, td, J = J_F-H = 9, J = 3 Hz, H_p), 6.68 (2H, t, J = J_F-H = 8 Hz, H_m), 6.24 (1H, d, J = 2 Hz, H_imid), 6.05 (1H, d, J = 2 Hz, H_imid), 5.70 (s, 2H, benzyl), 2.48 (6H, s, J_Pt-H = 13 Hz, DMSO), 1.25 (3H, s, J_Pt-H = 72 Hz Me); δ_F: -114.80 (1F, s), -117.56 (1F, s, J_Pt-F = 56 Hz); δ_Pt: -4196ppm.

**References**